System Studies for the ADTF:
Target and Materials Test Station

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Summary
To meet the objectives of the Advanced Accelerator Applications (AAA) program, the Accelerator Driven Test Facility (ADTF) provides a world-class accelerator-driven test facility to:

- Provide the capability to assess technology options for the transmutation of spent nuclear fuel and waste through a proof-of-performance.
- Provide a user facility that allows testing of advanced nuclear technologies and applications, material science and research, experimental physics, and conventional nuclear engineering science applications.
- Provide the capability, through upgrades or additions to the ADTF accelerator, to produce tritium for defense purposes, if required.
- Provide the capability, through upgrades or additions, to produce radioisotopes for medical and commercial purposes.

These missions are diverse and demand a facility with significant flexibility. In order to meet them, it is envisioned that we construct two target stations; the Target & Materials Test (TMT) station and the Sub-Critical Multiplier (SCM) test station. The two test stations share common hot-cell facilities for post irradiation examination. It is expected the TMT will come on line first, closely followed by the SCM. The TMT will provide the capability to:

- Irradiate small samples of proposed ATW fuels and materials at prototypic flux, temperature and coolant conditions (requires intense source of neutrons).
- Perform transient testing.
- Test both liquid (lead-bismuth) and solid spallation targets with either water, sodium, or helium coolant.
- Test generation-IV fuels for advance nuclear systems (requires high intensity thermal flux).
- Irradiate fission product transmutation targets.
- Test advanced fuel and coolant combinations, including helium, water, sodium and lead-bismuth.
- Produce isotopes for commercial and medical applications.
- Perform neutron physics experiments.

The SCM will provide the capability to:

- Irradiate large samples of proposed ATW fuels and materials at prototypic flux, temperature and coolant conditions (requires intense source of fast neutrons).
- Provide significant throughput of irradiated fuel for separations testing at adequate scale.
- Use the target technology demonstrated in the TMT.
- Test and demonstrate the safe coupling and operation of an accelerator driven sub-critical multiplier.
- Perform neutron physics experiments.

By it's nature, the TMT neutron source is driven by the spallation process. The amount of fuel to be tested is small, and will offer little or no multiplication. The SCM however is a 100 MW capable sub-critical reactor. The neutron source in this case is derived primarily from the fissioning of fuel. The remainder of this paper focuses on the description of the TMT station, and the scoping analyses that have been performed to support the pre-conceptual design. The SCM development is discussed in a separate paper.

Site Layout

As noted above, the TMT provides the test environment for materials and fuel experiments, coolant and target technology experiments, and provides the potential for isotope production. The SCM however provides the test environment for demonstration of accelerator/multiplier coupling, irradiation of significant quantities of fuel and the eventual transition to an actinide core. Figure 1 displays the site layout showing the relative positions of the accelerator, TMT and SCM. The current plant arrangement will allow the target stations to be offset so as to not to interfere with an upgrade path to extend the accelerator tunnel and construct future target stations. In addition, the SCM and TMT stations will be arranged such that the beam will enter at the same elevation. The SCM and TMT stations are arranged to allow a single hot cell facility to support the operational needs of both stations for post irradiation examination and material handling.

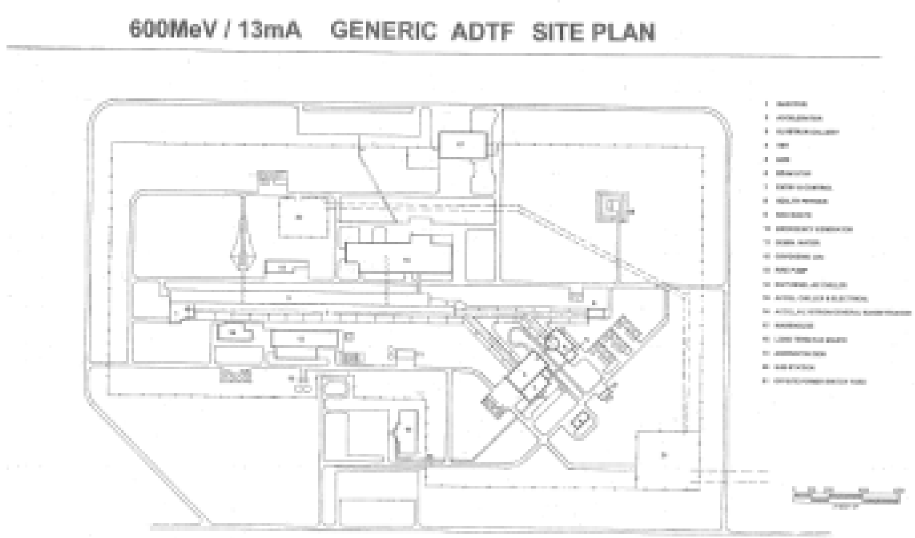

Figure 1. ADTF Site Plan

<u>TMT Station Overview</u>

The (TMT) Station is comprised of a spallation neutron source driven by a continuous proton beam operating at 600 MeV and 13 to 20 mA of current. The configuration is designed to provide optimum flexibility in the testing of materials, coolants, targets and fuels that are envisioned for use in accelerator transmutation of waste systems. In addition this system provides a versatile irradiation environment that allows for testing of advanced nuclear systems such as generation-IV fuels, and production of isotopes for commercial and medical use. The concept consists of a centrally located irradiation chamber that contains the spallation neutron source (target) and surrounding reflectors, moderators and closed coolant loops. The entire chamber is shielded with 5 m of steel and concrete to protect the workers. The proton beam, target and materials tests are all brought into the cell horizontally or vertically (Figs. 2 and 3). This provides for a simple, straightforward beam transport system from the accelerator to the irradiation chamber. In addition, the mechanisms for implementing a horizontal target and multiplier insertion configuration are a demonstrated technology based on existing and planned facilities. At the completion of an irradiation cycle, target and/or test components are moved into and out of the irradiation chamber from adjoining hot-cells. All primary heat-removal equipment resides in the hot-cells providing for safe operation and maintenance similar to operations at the Spallation Neutron Source.

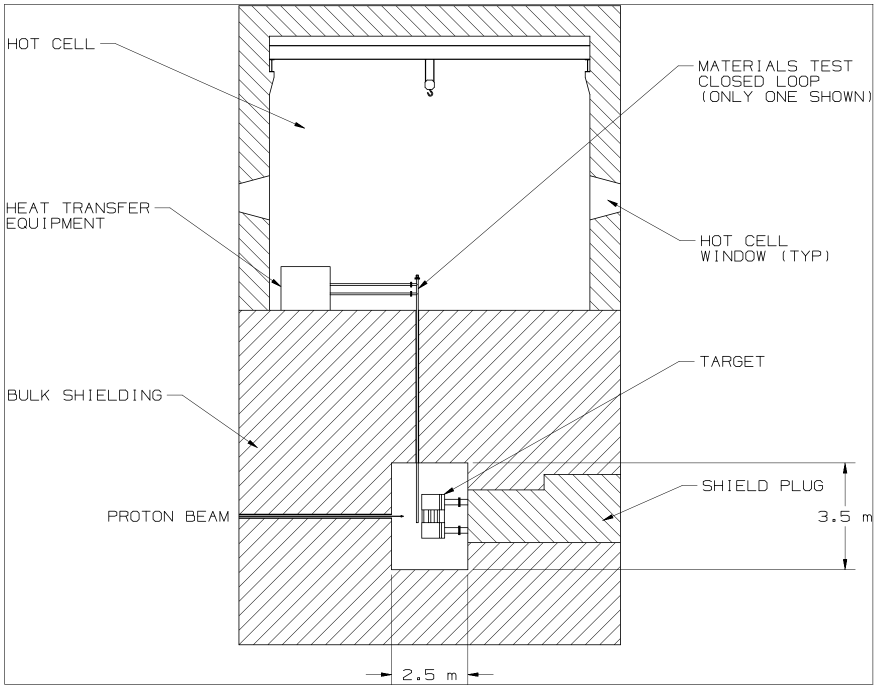

Figure 2. TMT Elevation View

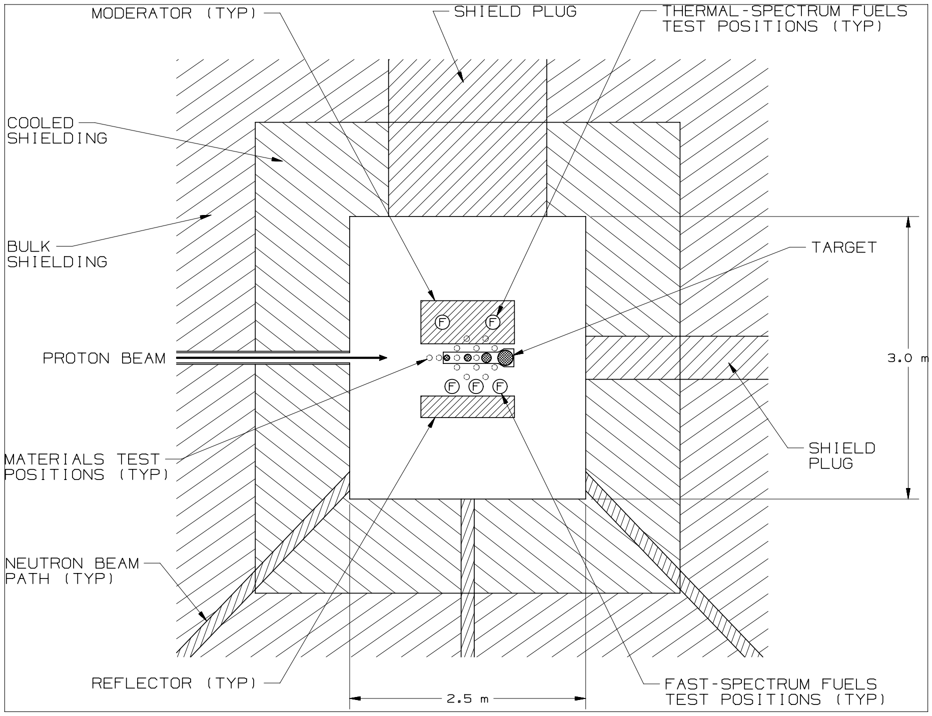

Figure 3. TMT Plan View

<u>Target Design Options</u>

To provide the optimum flexibility for both fast spectrum and thermal spectrum irradiations, two major target/reflector/moderator configurations are being investigated, wing geometry and annular geometry (Fig. 4). The base-case system employs a reflector adjoining the neutron source in a wing geometry where the neutron source is centrally located, and the test region sets off to the side (Fig. 3). Neutrons produced in the target by spallation, leak radially outward into the adjoining reflector. Using this geometry and the accelerator providing a continuous flow of protons at 600 MeV, 13mA, a fast spectrum neutron flux of 1×10^{15} n/cm^2/s is generated in the reflector. Within this region closed loops are used to irradiate fuels and materials in either sodium, lead-bismuth or helium coolant. In addition to the fast spectrum, a thermal-spectrum is possible by replacing the reflector with a moderator. In this region thermal fluxes of up to 4 x 10^{14} n/cm^2/s are possible, providing an excellent environment for the irradiation of advanced fuels and materials for next generation reactors. For example, advanced fuel for a graphite moderated, helium cooled system can be tested using this configuration.

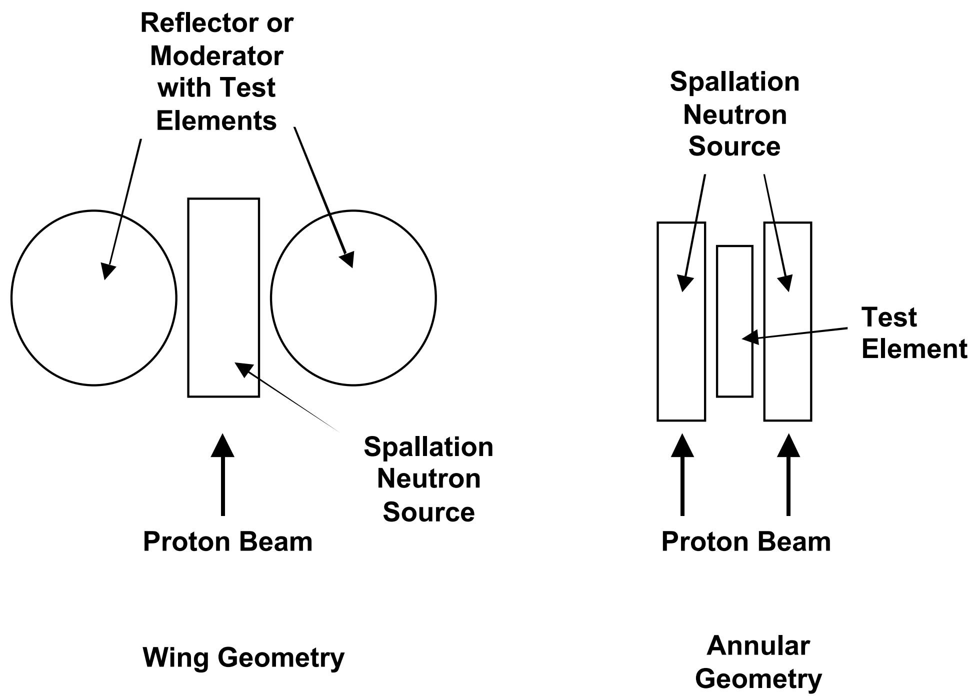

Figure 4. Target Design Geometry Options

An alternate target system being investigated uses annular geometry. As shown in Fig. 4, the proton beam for this system in annular or "donut" shaped. Neutrons produced in the target region leak inward into the centrally located test region. Here fuel and materials are located in a closed loop cooling system. To implement this system the target/test assembly shown in Fig. 3 would be replaced with an annular system, and the beam expansion magnets reconfigured to produce the annular beam. Using this system calculations show that the flux intensity can be doubled over that of the wing geometry. Details of the two target options are given below.

Wing Geometry Design Studies

For the wing geometry several spallation materials were analyzed. These include Lead-Bismuth eutectic (LBE), sodium-cooled tungsten, and helium-cooled tungsten. A generic target concept is illustrated in Fig. 5, where the target consists of a number of parallel tubes connecting a lower and upper plenum.

This concept is primarily developed for a liquid LBE target where the LBE flows from the lower plenum to the upper plenum through a series of parallel tubes. The same concept can be used for the sodium cooled or helium cooled tungsten concepts as well. For the solid target option, the tubes would house concentric tungsten cylinders with the coolant flowing in the gaps (see Fig. 6). It is also conceivable that the tubes may be used to contain a packed-bed of tungsten spheres for the helium cooled target option.

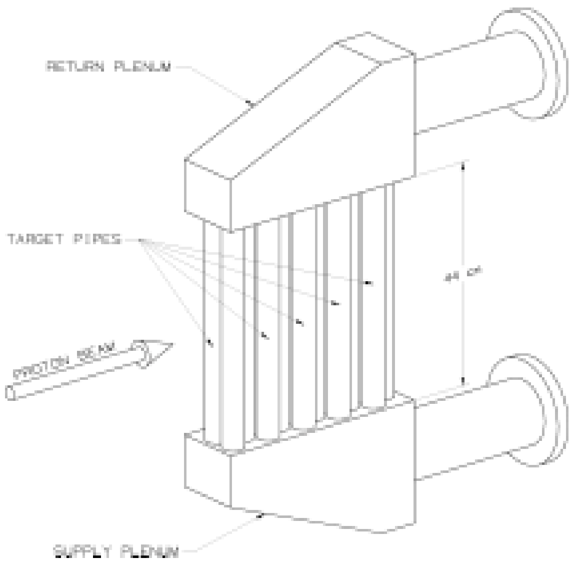

Figure 5. Generic Target Arrangement for Wing Geometry

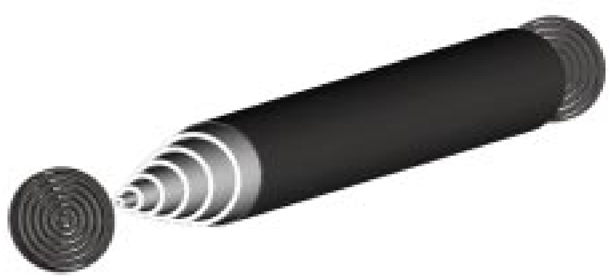

Figure 6. Solid Tungsten Target Design Option

Scoping calculations indicate that thermal-hydraulic limits can easily be met with the parallel tube concept. Because of the excellent liquid-metal heat transfer coefficients, the LBE target and the sodium-cooled tungsten target offer the highest potential power density and therefore the highest neutron intensity. Because the LBE target material can be drained for maintenance, this option simplifies the target extraction and replacement. In addition the LBE material is re-used therefore reducing the waste stream significantly over the solid target options. For the helium-cooled tungsten option, analytical studies show that a significantly larger beam spot is required in order to reduce the power densities to acceptable levels. Very high pressure and velocity are needed to approach the performance of a liquid metal cooled target so it has been dropped for further consideration at this time.

For the LBE target the maximum LBE velocity is set to 2 m/s to avoid erosion. The inlet LBE temperature is 200°C. The peak surface temperature (in contact with LBE) is set to 550°C because of corrosion control concerns. At 2 m/s, which is the current baseline, the maximum allowable current density is 66 mA/cm^2. If the velocity limit can be increased to 3 m/s, the beam spot size can be reduced resulting in a maximum allowable current density of 86 mA/cm^2.
The minimum LBE velocity needed to cool the different tubes is also calculated. The results show that the front tubes require a velocity of 2 m/s whereas the back tubes can be cooled using LBE velocities less than 0.5 m/s. If the flow distribution is tailored to power distribution using orifices, the average LBE exit velocity is 320°C.

The structural material containing the LBE target must be replaced frequently as it endures a great deal of radiation damage. Extending the database developed for the Accelerator Production of Tritium project, a structural design criterion will be developed to address the target structure and the high-energy portion of the neutron spectrum near the spallation target. Based on materials irradiation data and structural design criteria, component-lifetime limits will be developed and implemented with adequate safety margin. Although the design is tailored to accommodate the need to frequently replace the components, engineering design and demonstration efforts will be aimed at maximizing the design lifetime of the components to maximize the facility availability.

A series of calculations were completed to assess the sodium-cooled tungsten target performance. The geometry is similar to the one shown in Fig. 5 except the coolant flows though a series of parallel tubes containing concentric tungsten cylinders (see Fig. 6). Thermal-hydraulic analyses were performed to investigate the maximum allowable current density. In all cases, a beam height (heated length) of 38 cm is used. The maximum temperature for the clad on the tungsten cylinders is limited to 600°C. The tube wall thickness is 0.9 mm and the clad thickness 0.125 mm. The sodium flow velocity in the gap between the tungsten cylinders, tungsten volume fraction (by varying the thickness of tungsten cylinders), the gap size (flow gap between the cylinders) and the tube size are changed for the 4 cases investigated. The results are summarized in Table 1. As shown in this Table, a sodium cooled tungsten target may reach a performance (in terms of allowable current density) similar to LBE target performance using a very tight thermal-hydraulic design. To achieve this performance, the sodium velocity must be increased to 5 m/s or higher through narrow 1mm gaps.

Table 1. Sodium-Cooled Tungsten Thermal-Hydraulics

CASE	**1**	**2**	**3**	**4**
Velocity (m/s)	4	5	4	4
Tungsten Fraction (%)	58.4	58.4	63.7	59.3
Channel gap (mm)	1	1	1	1.25
Tube Diameter (mm)	40	40	43	49
Current density (mA/cm^2)	53.0	65.2	43.0	52.3

The neutronics performance of the LBE and sodium-cooled tungsten targets was investigated using the compact target geometry described above. All calculations assumed a 600 MeV, 13.3 mA proton beam. In these simulations, a beryllium reflector is used on one side of the target to achieve the thermal spectrum. To achieve the fast spectrum, a Nickel reflector is used. To make the comparison, thermal fluxes are determined by averaging over a 4-L volume in the moderator. The fast spectrum fluxes are determined by averaging over a 2-L volume in the Nickel reflector. These volumes are reasonable values for the purpose of fuel and materials irradiations. The thermal spectrum is defined by neutron energies less than 0.625 eV, whereas the fast spectrum is defined by neutron energies greater than 0.1 MeV. The resulting total, fast and thermal neutron fluxes are given in Table 2 for both target materials.

Table 2. Neutronics Performance of the Sodium-Cooled Tungsten Target

	Moderator Fluxes (n/cm^2s)		Reflector Fluxes (n/cm^2s)	
	Thermal Flux	Total Flux	Fast Flux	Total Flux
LBE	3.6×10^{14}	1.1×10^{15}	7.3×10^{14}	9.7×10^{14}
Sodium-Cooled Tungsten	3.0×10^{14}	1.0×10^{15}	7.3×10^{14}	9.8×10^{14}

As shown in the table, the fluxes for the two materials are very similar in magnitude. The thermal flux achievable over a 4-L volume in the moderator is 3 x 10^{14} n/cm^2-s. In the reflector, the fast flux averaged over the 2-L volume is 1 x

10^{15} n/cm^2-s. The thermal flux levels are approximately one order of magnitude higher than what is experienced in a thermal power reactor. Thus, this would be an excellent environment for testing Generation-IV reactor fuels and obtaining high burn-up quickly. For the fast spectrum, the fuel designers desire a flux intensity that is about 3 times higher in order to obtain burn-up performance in a reasonable amount of time.

Because of the need for a compact target, and the ease of maintenance for the LBE target and the reduced waste stream, it has been chosen for the base case design. Nevertheless, the facility will have the capability to test both the sodium-cooled tungsten target and a helium cooled target if the need arises.

Annular Target Geometry Option

Because of the need for a more intense neutron flux for irradiating fast spectrum fuels and materials above what is achievable with the wing geometry, the annular geometry was investigated. The conceptual layout of this target geometry is shown in figure 7. For this option, the beam is rastered into an annulus (beam spot inner and outer radii are approximately 5 and 15 cm, respectively). This spot matches the location of the spallation target with adequate margin for beam position. Neutrons produced in the target leak inwards towards the test section as well as radially outwards towards the reflector. Analyses show that at 600 MeV, 13 mA, a fast spectrum neutron flux of 2 x 10^{15} n/cm^2-s is achievable in the test section. Therefore for a given beam power, this target option doubles the neutron intensity over that of wing geometry.

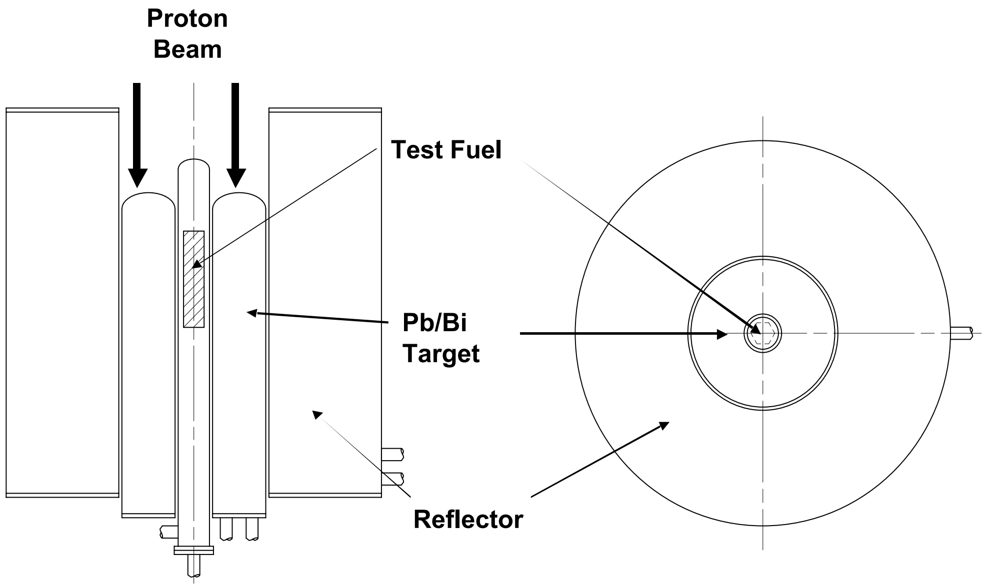

Figure 7. Annular Target Geometry

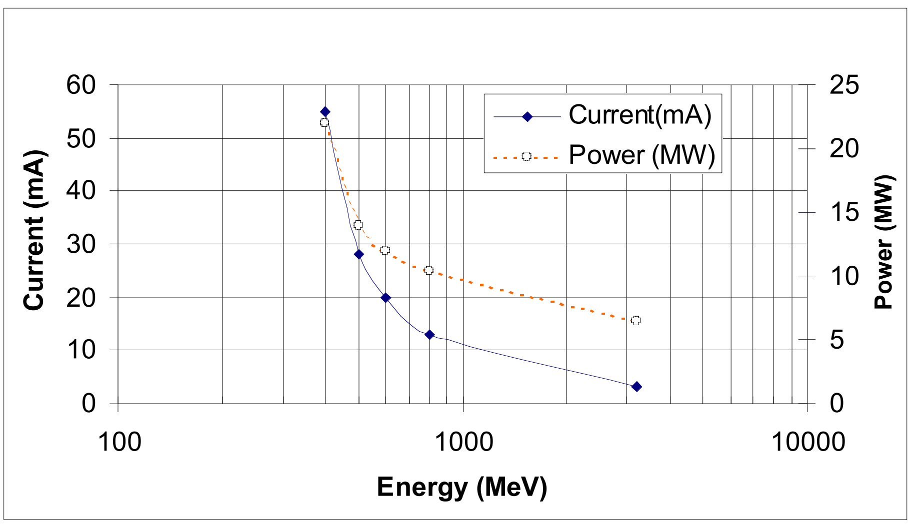

Figure 8. Beam Current vs. Energy to Achieve $3x10^{15}$ n/cm^2/s

Although the flux can be doubled using this innovative geometry, it is still below the $3x10^{15}$ n/cm^2/s value desired by the fuel and materials researchers.

Therefore scoping physics calculations were performed to determine the beam current and energy required to reach a fast neutron flux of 3 $x10^{15}$ $n/cm^2/s$. As shown in figure 8, using the annular target geometry a 600 MeV beam, 20 mA of current can achieve this flux level. Higher beam energies are more efficient at producing neutrons and therefore the beam power requirement decreases with energy. A beam energy of 600 MeV offers the benefit that the power density in the target reaches a balance between the bragg peak and the spallation peak. Thus from a power density standpoint, and therefore target size, this energy offers an optimum. From a cost standpoint, the lower beam energies are preferred because the accelerator is shorter. The 600 MeV proton energy offers a reasonable compromise between target engineering and efficiency, and cost.

Table 3 summarizes both the flux, radiation damage and burn-up of fuel for this system. Very high flux intensities and fuel burn-ups are achievable. Assuming a fuel region in the test section that is representative of a 19 rod bundle a very uniform flux distribution is calculated both axially and radially. Spectra are similar to that of fast reactors with the addition of a high energy tail caused by the spallation neutrons.

Table 3. Neutronic Performance of the Annular Target Option

Parameter	**Value**
Total neutron flux in the test section	3.3 $x10^{15}$ $n/cm^2/s$
Fast neutron flux (greater than 0.1 MeV) in the test section	3.1 $x10^{15}$ $n/cm^2/s$
High energy neutron flux (greater than 20 MeV) in the test section	1.3 $x10^{15}$ $n/cm^2/s$
Fuel Burn-up in 300 full power days	
Minor Actinide Fuel	10.0 atom % / year
Plutonium-239 based fuel	15.5 atom % / year
Uranium-235 based fuel	11.9 atom % / year
Radiation damage in steel in 300 full power days	75 dpa/y
Helium production in steel in 300 full power days	500 appm/y

Calculations of the radiation damage are also shown in the table. Here we observe that for a 300 day year of operation, 75 displacements per atom (dpa) of damage are realized in the test section. This is very similar to what is expected in a fast reactor with similar flux intensity. However, in addition to this damage, 500 atomic parts per million (appm) of helium are generated in the structural materials. Thus although the very high fluxes and burn-ups are achievable the helium production is high for cladding materials and needs to be reduced in order for the pins to achieve higher burn-ups before the cladding reaches it's end-of-life. Based on studies of ADS systems our goal is to achieve no more than 75 appm helium per year of irradiation. To achieve this reduced helium production, the we are investigating the use of buffers between the spallation target and the test section.

Heat Removal

One of the functions of the TMT station is to test various target technologies which may employ one of the coolants discussed above. It is desirable to keep the secondary loop of the heat removal system fixed, independent of the coolant used in the primary system. One coolant that is compatible with all the current options considered is helium. Thus, we envision using helium as the coolant in the secondary loop. There are two concerns with the helium secondary loop:

1. The size and weight of the heat exchangers, and
2. The potential for blowing the liquid metal out of the target by high pressure helium in case of a heat-exchanger tube break.

To circumvent the second issue, it is currently envisioned that a stagnant liquid metal jacket would be used around the heat exchanger tubes for the liquid metal-cooled systems.

As part of the pre-conceptual design, a sizing study for a LBE-to-helium heat exchanger, assuming a stagnant LBE jacket around the heat exchanger tubes was performed. In this study, the LBE velocity in the heat exchanger tubes is limited to 0.7 m/s. Helium pressure is set to 20 bars. The lead-bismuth enters the heat exchanger at 315°C and exits at 200°C. The thermal-load is 5 MW (corresponding to a 8 MW beam power). The resulting heat exchanger is approximately 0.8 m in diameter and 4 m in length which is an acceptable size for the facility.

Safety

The TMT design concept simplifies the operational aspects of the facility while providing adequate level of safety. Using a "safety by design" approach, the target and materials beam shutdown systems are designed with the maximum reliance on passive safety features. Natural circulation of coolants for both the target and fueled loops and diverse cooling mechanisms provide adequate protection in the event of accidents. In the event of a leak or break in either the target or test element pressure boundaries inside the irradiation chamber, the loss of vacuum will passively shut down the beam. This shutdown mechanism provides a back up to a highly reliable active shutdown system.

Conclusion

The ADTF TMT pre-conceptual design studies have been performed to determine the optimum target geometry and materials for irradiations. Both wing geometry and annular geometry have been considered for the spallation neutron source as well as LBE and tungsten targets. Calculations show that the wing geometry offers excellent flexibility for the irradiation of materials especially in a moderated spectrum. However, in order to achieve fast flux levels that are of interest to fuel and material designers, the annular geometry performs significantly better, with a doubling of the flux intensity. The results show that for a 600 MeV proton beam with a current of 20 mA, a fast neutron flux level of $3x10^{15}$ n/cm^2/s is achievable. Future studies will be performed to reduce the helium production in the test section to more representative levels expected in the ADS systems. For the target material, a LBE target is preferred over that of sodium-cooled tungsten and helium cooled tungsten. This target provides a very high power density capability and high neutron leakage. In addition the waste stream is reduced over the solid target options because the target structure only needs to be replaced. Nevertheless the facility will provide the capability to test the various target options in order to support the transmutation research program.